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TIDES IN THE BAY OF FUNDY

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The greatest known rise and fall of tide occurs in the Bay of Fundy, the arm of the Atlantic that separates the Canadian province of Nova Scotia from its sister province of New Brunswick and from the State of Maine. At its head the Bay of Fundy forks into two inlets, in the southern one of which, Minas Basin, the tide rises a vertical distance of from forty to fifty feet in a period of six hours and falls the same distance in the following period of six hours.

That the tide in the Bay of Fundy is characterized by a very considerable rise and fall has been known for many years. In some of the older publications, however, the figures given for this rise and fall appear to have been affected by a "factor of dramatic effect." As an example, we find in the *Astronomy* of Sir John Herschel¹ the statement that "in some places the tide-wave, rushing up a narrow channel, is suddenly raised to an extraordinary height. At Annapolis, for instance, in the Bay of Fundy, it is said to rise 120 feet." As given in the tide tables² the rise and fall of the tide at Annapolis is, on the average, 25 feet increasing to 29 feet at times of spring tides.

In the upper parts of the Bay of Fundy, in consequence of the great range of the tide, the shores at low water present a bare appearance, exposing to view wide expanses of mud flats. This condition greatly affects communication by water. "As regards navigation, the numerous small steamers in the upper part of the bay have to make their calls at high water and leave promptly, as all the wharves dry at about half tide. Schooners are accommodated by lying on a bench of mattress-work, against the wharves, while the tide is down."³

The configuration and hydrographic features of the Bay of Fundy are shown in Figure 1, which is based on Chart No. 1412, issued by the U. S. Hydrographic Office. The mouth of the bay, defined by a line drawn from Jebogue Point on the south to Point of Main on the north, has a width of 76 geographic miles and an average depth of 280 feet, reckoned from mean sea level. At Cape Chignecto, where the bay forks, the width is 25 miles and the average depth 130 feet, and above Cape Chignecto the contraction in width and shallowing in depth take place even more rapidly.

It is to this gradual narrowing of the bay and its lessening depth from mouth to head that the very considerable rise and fall of the tide in the

¹ J. F. W. Herschel: *Outlines of Astronomy*, 6th edit., London, 1859, p. 531.

² Tide Tables, United States and Foreign Ports, for the year 1922, *U. S. Dept. of Commerce Serial No. 163*, U. S. Coast and Geodetic Survey, Washington, D. C., 1921, p. 335.

³ W. B. Dawson: *Tides at the Head of the Bay of Fundy*, Ottawa, 1917, p. 3.

upper reaches had generally been ascribed. "The greater rise of the tides in the upper part of this bay is attributed to its narrowing funnel form, and its shallowing bottom cooping up the tidal wave as it advances up the bay."⁴

THE RANGE OF THE TIDE

The extent of the rise and fall of the tide, or more precisely, the range of the tide, increases from the mouth of the bay to its head. Taking the Nova

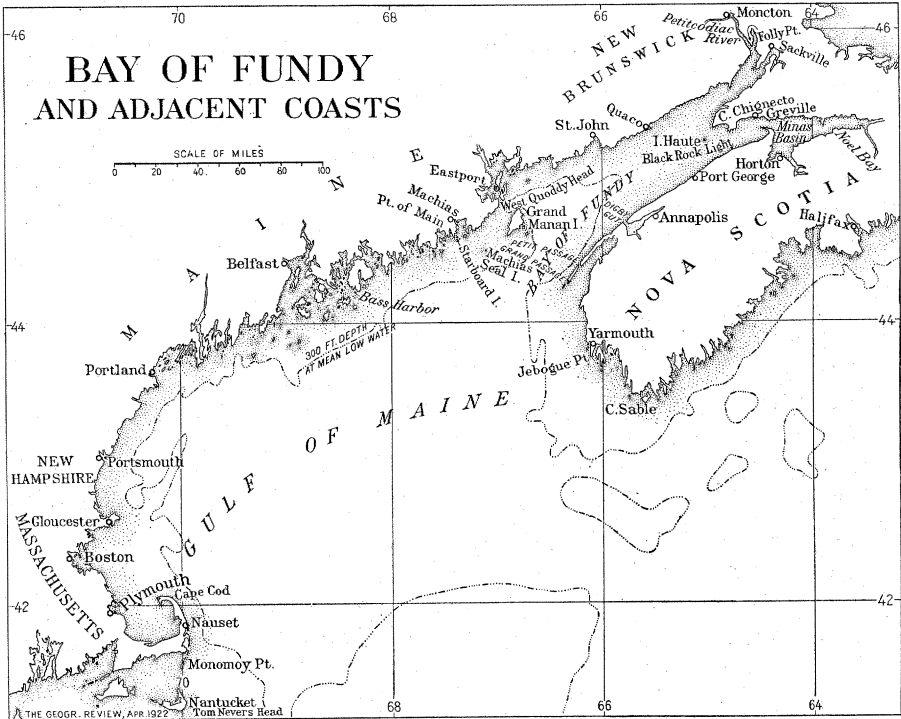


FIG. 1

Scotia shore, we have a mean range of 9.1 feet at Cape Sable, 14.0 feet at Yarmouth, 18.2 feet at Grand Passage, 24.1 feet at Digby Gut, 27.8 feet at Port George, 31.5 feet at Black Rock Light, 42.0 feet at Horton Bluff and 44.2 feet in Noel Bay.⁵ At times of new and full moon, when the so-called spring tides occur, the range of the tide is about 14 per cent greater, and at such times the tides in Noel Bay have a rise and fall of about 50.5 feet.⁶

On the north shore a similar condition prevails, the range of the tide

⁴ Robert Chalmers: Report on the Surface Geology of Eastern New Brunswick, Northwestern Nova Scotia, etc., Report M of *Ann. Rept. Geol. Survey of Canada*, Vol. 7 for 1894, Ottawa, 1895, p. 16.

⁵ Tide Tables . . . 1922, p. 335.

⁶ *Ibid.*, p. 335.

increasing from the mouth of the bay to its head. This increase becomes even more striking if we begin with the tide at Tom Nevers Head on Nantucket Island and go up the coasts of Massachusetts, New Hampshire, Maine, and New Brunswick, which form the western and northern shore of the Gulf of Maine and Bay of Fundy. For the mean range of the tide we have 1.2 feet at Tom Nevers Head, 3.7 feet at Monomoy Point, 6.0 feet at Nauset Harbor, 8.9 feet at Gloucester, 10.2 feet at Bass Harbor, 15.7 feet at West Quoddy Head, 20.9 feet at St. John, 26.3 feet at Quaco, 39.4 feet at



FIG. 2—Low water, mouth of Petitcodiac River, Bay of Fundy. Government Wharf, Hopewell Cape. Folly Point seen in the distance. At spring tides the water falls about 13 feet lower than is seen here. (Courtesy of Canadian Tidal and Current Survey).

Folly Point, and 41.2 feet at Moncton.⁷ Here likewise the spring range of the tide is about 14 per cent greater than the mean range.

It is evident that the effect of the converging shore lines and gradual slope of bottom tends to increase somewhat the range of the tide in the upper parts of the bay. But it is likewise evident that these features cannot be wholly responsible for the increase in range from less than 10 feet at the mouth to more than 40 at the head. There is involved some factor other than the "cooping up of the tidal wave as it advances up the bay." For in many other bays we have somewhat similar features without anything like corresponding increases in range of tide. Thus at the mouth of Delaware Bay we have a mean tidal range of 4.7 feet; and at Philadelphia,

⁷ *Ibid.*, pp. 335-338.

where the cross section of the tidal waterway has decreased very considerably, the range of the tide is but 5.3 feet.⁸

A close examination of the ranges of the tide brings to light the fact that, relative to the axis of the bay, a point on the southern shore has a greater range of tide than the corresponding point on the northern shore. Thus the tide tables give as mean ranges of the tide 14.0 feet for Yarmouth against 12.9 feet at Starboard Island; 19.3 feet in Petit Passage against 15.7 feet at West Quoddy Head; 27.8 feet at Port George against 26.3 feet at Quaco.⁹

This increase in the range of the tide on the southern shore is brought about by the rotation of the earth, in consequence of which all moving bodies are impressed with a force deflecting them to the right in the northern hemisphere and to the left in the southern hemisphere. On the flood tide the water entering the Bay of Fundy is deflected to the right or southern shore; hence high water here is raised somewhat higher than on the northern shore. On the ebb tide the moving water is again deflected to the right; but now it is the northern shore that is to the right of the moving water, and hence low water is somewhat higher on the northern than on the southern shore. The tide therefore rises higher and falls lower on the southern shore, giving a greater range here than on the northern shore.

RATE OF RISE AND FALL

In its rise and fall the tide does not move at a uniform rate. Beginning at low water the rise at first takes place very slowly but at a constantly increasing rate, so that about three hours after low water the tide has acquired its greatest rate of rise. From this time the rise begins to take place at a constantly decreasing rate until high water is reached. A similar cycle then begins in the falling direction, the rate of fall increasing gradually for about three hours, when it is greatest. The tide then continues its fall at a constantly decreasing rate until low water is reached.

If the rise and fall of the tide be represented graphically by plotting the height of the water at successive intervals of time, say every half hour or hour, the curve of the tide will approximate the well known form of the sine or cosine curve. This is brought out in the accompanying diagram of the rise and fall of the tide on August 13, 1862, at Eastport, Maine, on the northern shore of the Bay of Fundy. The curve was drawn by plotting the heights of the tide at every half hour as determined from an automatic tide gauge record.

The variations in the rate of rise and fall of the tide from low water to high water and from high water to low water stand out clearly in the diagram. The most rapid rise takes place midway between low water and high water, and the most rapid fall midway between high water and low water;

⁸ Tide Tables . . . 1922, p. 344.

⁹ *Ibid.*, pp. 335-336.



FIG. 3



FIG. 4

FIG. 3—Low water, mouth of Petitcodiac River, Bay of Fundy. Government Wharf, Hopewell Cape. (Courtesy of Canadian Tidal and Current Survey.)

FIG. 4—High water, mouth of Petitcodiac River, Bay of Fundy. Government Wharf, Hopewell Cape. High tide occasionally covers the wharf shown here. (Courtesy of Canadian Tidal and Current Survey.)

and in both cases this is about three hours from the time of high or low water.

From the theory of the cosine curve we find likewise that the most rapid change of elevation takes place midway between the highest and lowest points; and it is of interest to compare the theoretical rate of most rapid rise or fall with that determined from actual observations. From Figure 5 we find that from 7:40 A. M. till 1:45 P. M., that is in a period of 6 hours and 5 minutes, the tide rose a total distance of 21.1 feet, with the most rapid rise occurring between 10 and 11 A. M., when the elevation changed by 5.0 feet. For a range of 21.1 feet in six hours and five minutes, the theory of the cosine curve gives 5.4 feet as the greatest change in elevation during one hour. The close agreement between the actual rise of 5.0 feet and the computed rise of 5.4 feet for a true cosine curve shows that the tide curve for Eastport does not deviate much from the cosine curve.

The rate of rise or fall of the tide evidently depends on the total rise and fall of the tide, increasing in direct proportion to the total range. In 1916 in the vicinity of Noel Bay, W. Bell Dawson¹⁰ measured a rise of 11.2 feet per hour occurring with a tide that had a total rise of 49.7 feet in a period of six hours and one minute. The theoretical most rapid hourly rise in a true cosine curve of the same range is 12.8 feet. In this connection it may be of interest to note that sixty years ago one of our encyclopedias had it that the Bay of Fundy was "remarkable for its extraordinary tides which rush up from the sea with such rapidity as sometimes to overtake swine feeding on shellfish on the shores."¹¹

TIME OF TIDE

In most bays and rivers the time of tide becomes later, in going upstream, at a rate dependent on the depth of the tidal waterway. Thus in Chesapeake Bay the time of tide at Turkey Point Light, which is about 165 geographical miles above the mouth of the bay, is 12 hours later than at Cape Charles Quarantine.¹² This gives the tidal wave a rate of advance of $13\frac{3}{4}$ geographical miles per hour.

The relation existing between the time of tide in the upper and lower reaches of a bay, such as Chesapeake Bay or Delaware Bay, is given approximately by the formula, $v = \sqrt{gh}$ where v is the velocity of the tidal wave, g is the acceleration of gravity, and h is the average depth of the tidal waterway. Applying this formula to the stretch of Chesapeake Bay from Cape Charles Quarantine to Turkey Point Light, we find, since the value of g for the latitudes of Chesapeake Bay is 32.15 feet per second, a value for h of 17 feet. This is an approximation to the average depth of that stretch of the bay.

¹⁰ Dawson, *op. cit.*, p. 10.

¹¹ New American Cyclopaedia, New York, 1858-1863, Vol. 8, p. 11.

¹² Tide Tables . . . 1922, pp. 345-346.

If we examine the times of tide in the Bay of Fundy we find a totally different state of affairs. While the time of tide becomes somewhat later in going upstream, this retardation in time is quite inconsiderable and has no such relation to the depth of the tidal waterway as given in the formula above. Thus from Machias Seal Island, near the mouth of the Bay, to Isle Haute about 77 miles upstream the difference in time of tide is but four minutes.¹³ This gives a velocity for the tidal wave of $19\frac{3}{4}$ miles per minute, which, in the formula connecting the velocity of the tidal wave with the depth of the tidal waterway that holds good for most bays and rivers, gives the impossible depth of over 100,000 feet. The average depth of the bay from Machias Seal Island to Isle Haute is approximately 200 feet.

Throughout the whole length of the bay the time of tide differs but little. From Grand Passage to Noel Bay at the upper end, a distance of 132 miles, the tide becomes later by only 1 hour 39 minutes, giving for the tide a rate of advance of $1\frac{1}{3}$ mile per minute, which in the formula connecting depth and velocity results in a depth of almost 600 feet.

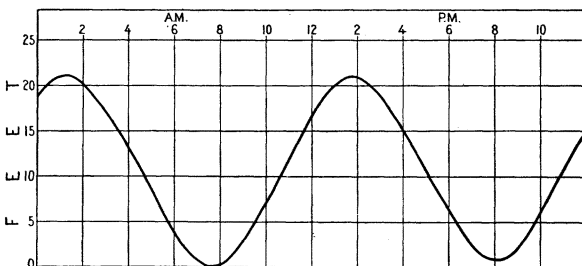


FIG. 5—Tide curve, Eastport, Me., August 13, 1862.

RELATION OF CURRENT TO TIDE

In so far as the time of tide is concerned it is evident that the tidal movement in the Bay of Fundy is quite different in character from that obtaining in Chesapeake Bay and in most bays and rivers. Further light on the character of this tidal movement may be obtained from a consideration of the tidal currents that accompany the rise and fall of the tide. From low water to high water an enormous quantity of water passes from the sea into the bay; and in the fall of the tide from high water to low water this vast amount of water passes out again to the sea. We may therefore expect tidal currents having considerable velocities.

From observations made over a considerable stretch of the Bay of Fundy by W. Bell Dawson,¹⁴ we find that the current stopped flooding about one hour after local high water and ebbing about an hour after low water. The strength of the flood current came about two hours before high water and the strength of the ebb current two hours before low water.

If we examine the relation obtaining between tide and current in a tidal

¹³ Tide Tables for the Eastern Coasts of Canada for the Year 1921, Canadian Tidal and Current Survey, Ottawa, 1920, p. 13.

¹⁴ W. B. Dawson: Tables of Hourly Direction and Velocity of the Currents and Time of Slack Water in the Bay of Fundy, etc., Ottawa, 1908.

waterway like Chesapeake Bay, we find that the strength of the current comes about the time of high or low water and slack water about three hours before high or low water. Whereas in the Bay of Fundy the current was running swiftest about midway between high and low water, in Chesapeake Bay the current is slack at that time; and the relation obtaining between tide and current in Chesapeake Bay is the one that characterizes most bays and rivers.

TYPES OF TIDAL MOVEMENTS

The differences that distinguish the times of the tide and the relation of tide to current in the Bay of Fundy from those in Chesapeake Bay arise from the fact that the tidal movements in these two bays are of different types—illustrating, in fact, the two principal types of tidal movements.

In Chesapeake Bay it was seen that going upstream the tide became progressively later from place to place. This is the “progressive wave” type. From theoretical considerations of this type of movement it follows that the rate of advance of the tide is a function of the depth and that in a uniform channel the range of the tide tends to decrease in going upstream. Furthermore, the current that accompanies the rise and fall of the tide should have its greatest velocity about the time of high and low water, slack occurring midway between high and low water.

This progressive wave type of movement is illustrated on a smaller scale by the ordinary wind waves with which we are familiar along the coast and in inland waters. If for the moment we call the crest of such a wave high water and its trough low water, it is evident that when this wave travels over a body of water the times of high and low water will progress regularly from one end to the other end of the body of water.

A wave of a totally different kind may also be made to travel through a body of water. Suppose we have a vessel, say a rectangular tank, partly filled with water: if we raise and then immediately lower one end, a wave will be started which puts into oscillation the whole body of water. But it will be noticed that high water will occur at one end when it is low water at the other end and that, for the body of water as a whole, high water will occur simultaneously for one half at the same instant that it is low water for the other half. This kind of movement is known as the “stationary wave” type.

If we examine the simple stationary wave movement as exemplified in a rectangular tank of water, we notice that the rise and fall of the water is nil at the middle and greatest at the ends, the range increasing from the middle to the ends. Furthermore, the horizontal motion of the water ceases at the time of high water and is greatest midway between the times of high and low water. This is brought out in Figure 6, which shows in diagrammatic form the positions of the surface of the water at the instants of high water and low water at each end.

When the surface of the water is in the position indicated by the line A B, it will be low water for half of the tank from A to M and high water for the other half from M to B. And later, when the surface of the water has assumed the position C D, it will be high water from C to M and low water from M to D. At M therefore the water neither rises nor falls; and the extent of rise and fall increases with the distance from M, so that at the two ends the rise and fall is greatest.

From the characteristics of the tidal movement in the Bay of Fundy, it is evident that we have here an example of the stationary wave type, in which the bay behaves approximately as one half of the rectangular tank of water shown in Figure 6. From the mouth to the head the time of tide is nearly simultaneous, the rise and fall increasing with the distance from the mouth.

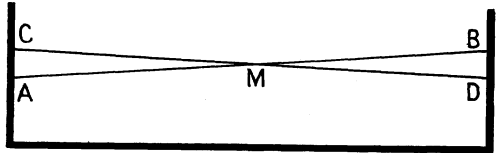


FIG. 6

A reason for the increased range of the tide in the upper reaches of the bay is therefore found in the character of the tidal movement. If we turn to other bodies of water in which the tidal movement is of the stationary wave type we shall likewise find an increase in the range of the tide from mouth to head. Thus in Long Island Sound, over the greater portion of which the tide is of the stationary wave type, the rise and fall of the tide increases from 2.0 feet at Montauk Point to 7.2 feet at Willets Point.

A further increase in the rise and fall of the tide at the upper end of the Bay of Fundy takes place because of the very considerable contraction in width and shallowing in depth. This increase in the range of the tide on account of decreased cross section takes place in both the stationary and progressive wave types of tidal movements. But even the co-operation of the causes adduced does not yet satisfactorily account for the enormous ranges of the tide found in the Bay of Fundy. A still further cause has been discovered somewhat recently in the period of oscillation of the water in the bay as a whole.

PERIOD OF OSCILLATION

If we start stationary waves in tanks of various lengths filled with water to different depths, it will be found that the time taken for a wave to travel from one end of the tank to the other, that is the period of the wave, depends only on the length of the tank and the depth of the water. In other words, for each body of water there is a natural period of oscillation which is a function of the depth of the water and the length of the basin in the direction of oscillation; and, if it is desired to maintain the stationary wave movement in our tanks of water, it is only necessary to apply a slight force, at intervals, to the tanks. But it will be found that if the force is applied at regular intervals, the rise and fall of the water in the tanks will be con-

siderably greater; and if the force be applied to the different tanks at regular intervals which in each case coincide with the natural periods of the different tanks, we shall have the maximum rise and fall of the water in each tank.

In inclosed bodies of water the stationary wave type of movement has been known and studied under the name of "seiche" since the time of F. A. Forel,¹⁵ who began his researches on the Lake of Geneva in the early seventies of the past century. The mathematical theory has been developed to a high degree, especially by Chrystal,¹⁶ who has made it applicable also to irregularly shaped basins. But nothing had been done in regard to bodies of water opening at one end into a very much greater basin, as exemplified by bays connected with the ocean.

In 1908 there appeared, independently, two publications in which the oscillation of bodies of water open at one end was treated. R. A. Harris,¹⁷ of the U. S. Coast and Geodetic Survey, investigated the matter in connection with his tidal studies; and, in Japan, Honda, Terada, Yoshida, and Isitani¹⁸ were led to the investigation in connection with earthquake studies. From these investigations it developed that bodies of water opening at one end into larger basins are capable of sustaining stationary wave movements of the character exemplified by the movement of the water in half of the tank, Figure 6, the formula for the period of oscillation in a rectangular basin of uniform depth being approximately $T = \sqrt{\frac{4L}{g h}}$ where T is the period of oscillation, L the length of the basin, g the acceleration of gravity, and h the depth of water.

It would appear reasonable to suppose that the width of the mouth of a bay has some influence on the period of oscillation; and such in fact the Japanese investigators found to be the case. By introducing a factor to take account of the width of the mouth, the approximate formula above becomes more exactly

$$T = \sqrt{\frac{4L}{g h}} \sqrt{1 + \frac{2}{\pi} \frac{b}{L} (0.9228 - \log_e \frac{\pi b}{4 L})}$$

where b is the width of the mouth of the bay, π and e having the usual significance.¹⁹

It is evident that, in computing the natural period of oscillation of the Bay of Fundy, the length of the bay and also its width will vary in accordance with the limits assigned to the bay; and this in turn will affect the value of the mean depth of the bay. Thus Honda and his colleagues²⁰

¹⁵ Forel's studies are summarized in his "Le Léman," Lausanne, 1892-1904, Vol. 2, pp. 39-213.

¹⁶ George Chrystal: On the Hydrodynamical Theory of Seiches, *Trans. Royal Soc. of Edinburgh*, Vol. 41, 1903-05, pp. 599-649.

¹⁷ R. A. Harris: Manual of Tides, Part V, Appendix 6 of *Rept. of the Supt. of the Coast and Geodetic Survey for 1906-1907*, Washington, D. C., 1907, pp. 467-482.

¹⁸ K. Honda, T. Terada, Y. Yoshida, and D. Isitani: Secondary Oscillations of Oceanic Tides, *Journ. College of Sci., Tokyo Imp. Univ.*, Vol. 24, 1908, pp. 1-110.

¹⁹ See Otto Krümmel: *Handbuch der Ozeanographie*, Vol. 2, Stuttgart, 1911, p. 163.

²⁰ Honda, *op. cit.*, p. 106.

found that by taking the mouth of the bay from Cape Sable to Cape Cod and the end of the bay at Port Greville, the period of oscillation was 13.0 hours; while by taking the mouth from Yarmouth to Machias the period of oscillation came to 11.6 hours. Taking the bay as extending from Grand Manan Island to Sackville, Krümmel²¹ derived a value of 12.46 hours. It is to be noted, however, that, while the value of the period of oscillation varies with the limits assigned to the bay, this value in every case approximates 12½ hours.

Now the mean value of the period of the tide is 12 hours 25 minutes, or 12.42 hours. We find, therefore, that the natural period of oscillation of the Bay of Fundy approximates very closely to the period of the tide. It appears, therefore, that the tides in the Bay of Fundy may be regarded as stationary wave oscillations of the whole body of water, the motion being sustained by the periodic ocean tide at the mouth of the bay. As we found in the case of our tanks of water, this oscillation is greatest when the period of the sustaining force is the same as the natural period of oscillation of the body of water.

It may, therefore, be concluded that the tidal phenomena in the Bay of Fundy are due primarily to the fact that the natural period of oscillation of the bay closely approximates the period of the ocean tide. This brings about a stationary wave movement with the greatest possible rise and fall of the water for the existing geographic features of the bay. In the upper reaches of the bay the range of the tide is further increased because of the considerable diminution of cross section brought about by the contraction in width and shoaling of bottom. The fact that some retardation in the time of tide occurs towards the head of the bay shows that there is some progressive wave movement present.

No account of the tide in the Bay of Fundy would be considered complete without at least a passing reference to the bore in the Petitcodiac River, at the head of the northern fork of the bay. Through a portion of this river the flood tide comes as a wall of broken and foaming water having "a height of perhaps two or three feet."²² This striking phenomenon is brought about by the resistance offered to the incoming tide by the river current and by the shallow and contracted channel at low water. A careful description of the bore has been given by W. Bell Dawson.²³

²¹ Krümmel, *op. cit.*, p. 319.

²² W. B. Dawson: Survey of Tides and Currents in Canadian Waters, Ottawa, 1899, p. 23.

²³ *Ibid.*, pp. 22-25.